THE EVAPORATION OF LIQUID DROPLETS IN HIGHLY TURBULENT GAS STREAMS

FINAL PROGRESS REPORT

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MAY 31, 1998

U.S. ARMY RESEARCH OFFICE

DAAH04-95-1-0231

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REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
May 31, 1998

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
The Evaporation of Liquid Droplets in Highly Turbulent Gas Streams

5. FUNDING NUMBERS
DAAH04-95-1-0231

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

North Carolina State University
Mechanical & Aerospace Engineering
Raleigh, NC 27695-7910

8. PERFORMING ORGANIZATION
REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING
AGENCY REPORT NUMBER

ARO 34119.2-EG

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

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12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Single acetone and heptane droplets were suspended from a hypodermic needle in turbulent air flow, and the Nusselt number was obtained from direct measurements of the droplet diameter and evaporation rate. Acetone was selected because it fluoresces when irradiated with ultraviolet laser radiation while heptane was selected because of its high volatility compared with water, methanol, and ethanol which were used previously. Planar laser induced fluorescence (PLIF) measurements were made to obtain qualitative concentration measurements of gaseous acetone in the boundary layer surrounding the droplet. The goal of these measurments was to give insight as to why the evaporation rate is increased by 50 % when the gas phase turbulence is increased from the laminar flow case to the case where the freestream turbulence is 10%. The use of acetone droplets required that the influence of humidity on droplet evaporation rate be considered. Measurements of the turbulence intensity of heated freestream air were also made. Finally, many modifications to improve the experimental apparatus were made during this research project.

14. SUBJECT TERMS
Evaporation, Liquid Droplets, Turbulent Gas

15. NUMBER OF PAGES
6

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

STATEMENT OF PROBLEM

Experimental measurements show that relatively mild gas phase turbulence can increase the heat/mass transfer rates from liquid droplets by as much as *30 - 50%* when compared to laminar flow evaporation rates at the same droplet Reynolds number based on mean upstream velocity. Thus, the objective of this research program is to better understand the physical processes governing the heat/mass transfer around single liquid droplets in turbulent air flow. One result of this effort is a heat/mass transfer correlation as a function of droplet Reynolds number, Prandtl number and gas phase turbulence intensity. The goals were to validate this correlation over a wider range of blowing numbers and to gain physical insight into why such mild gas phase turbulence has such a large effect on evaporation rate. Recently, flow visualization studies of the concentration boundary layer around acetone droplets and naphthalene spheres were conducted to address this second goal.

SUMMARY OF RESULTS

As mentioned above, the objective of this research program is to gain a physical understanding of the heat/mass transfer process for turbulent gas phase flow around single liquid droplets. Over the past three years experimental measurements made in the well controlled and characterized turbulent air flow in the test section shown in Figure 1 indicate that the evaporation rate is function of gas phase turbulence parameters in addition to droplet Reynolds and Prandtl number. Droplet diameter, mean air velocity and air temperature were varied independently to determine their effects on droplet evaporation rate. The measurements indicate that relatively mild gas phase turbulence (≈ 5 - *10%* turbulence intensity) can increase the heat/mass transfer rates from liquid droplets by as much as *30 - 50%* when compared to laminar flow evaporation rates at the same droplet Reynolds number based on mean upstream velocity. A heat transfer correlation which accounts for gas phase turbulence level was developed,

$$Nu_f\left(1+B_H\right)^{0.7} = 2 + 0.58\,\mathrm{Re}_{\mathrm{mod}}^{1/2}\,\mathrm{Pr}_f^{1/3}\left[1+0.07TI^{0.843}\right] \tag{1}$$

for the ranges, $50 < Re_{mod} < 1500$, $0.7 < Pr_{mix,f} < 1.0$, $0 < B_H < 0.14$, $0 < TI < 12\%$. This correlation degenerates to existing published laminar flow correlations with excellent agreement when no gas phase turbulence is present. Here B_H is the mass transfer number (or B number) based on enthalpy. Water, methanol, ethanol, acetone, hexane and heptane liquid droplets were used in generating this correlation (Yearling (1995), Jobin (1997)). Water, methanol, ethanol and acetone have since been discarded as evaporating liquids due to, low B number for water, water vapor absorption of the alcohols and the low surface temperature of acetone droplets which may lead to water vapor condensation (dew point –5 C) on the droplet surface. Wind tunnel air humidity measurements are now made prior to each evaporation rate measurement and test conditions are set so that water vapor condensation does not occur.

A new focus was initiated recently to access whether high surface blowing (i.e. high B number) isolates the droplet from the free stream gas phase turbulence. Some earlier

measurements (Jobin, (1997)) seem to indicate that high blowing negates the augmentation due to gas phase turbulence. Unfortunately, heated air is required to attain high B numbers and the calibration of the hot wire anemometer (used to measure mean velocity, and thus Reynolds number) becomes suspect in heated air. At this point the data suggesting this phenomena are somewhat inconsistent and thus need further validation, but it does seems physically plausible that high surface blowing would isolate the droplet surface from the free stream turbulence. Further studies are continuing to investigate whether high blowing does isolate the droplet.

A number of changes were made to the experimental apparatus in an effort to improve accuracy. Originally, hot wire anemometry was used to characterize the gas phase turbulence to which the droplet is exposed. Presently, a fiber optic probe based single component laser Doppler velocimeter (LDV) is being used to characterize the gas phase turbulence in the test section. Now no calibration is necessary and the turbulence in high temperature air can be measured non-intrusively. In addition, a completely redesigned syringe pump using a precision micrometer barrel as its basis is used to supply fluid to the liquid droplets in balance to that which evaporates such that the droplet retains the same diameter while measurements are made. The goal of these changes is to limit the experimental uncertainty to ±10%. Recent measurements using this redesigned facility for suspended heptane droplets are shown in Figures 2 and 3 below.

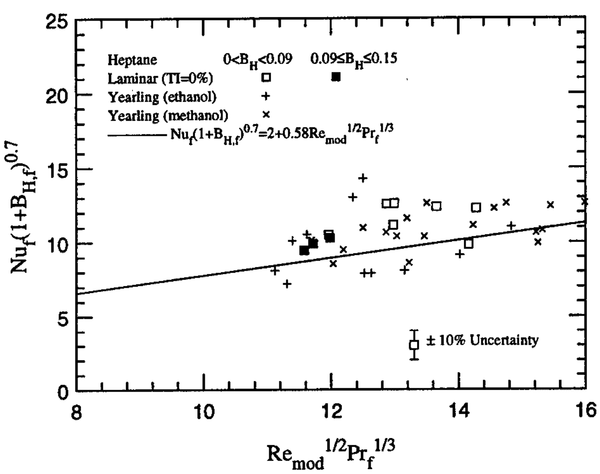


Figure 2. Laminar flow measurements

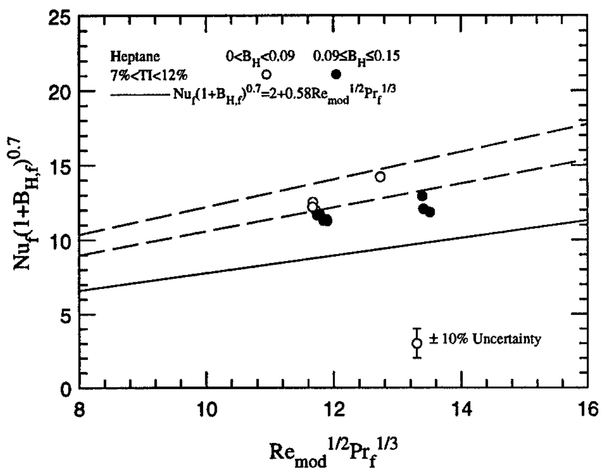


Figure 3. Turbulent flow measurements

The square symbols shown in Figure 2 denote measurements made in laminar flow using the LDV system and the redesigned syringe pump over two blowing number ranges. Also included in this figure are the data of Yearling (1995), using ethanol and methanol droplets, and the correlation (solid line) for droplet evaporation in laminar flow by Renksizbulut and Yuen (1983). The data are consistent which suggests that the new system is operating correctly. Figure 3 shows recent measurements in turbulent flow (7% < TI < 12%) over two blowing number ranges. The lower and upper dashed lines represent the correlation given by Eq. (1) for a turbulence intensity of 7 and 12%, respectively. The low blowing cases (opened circles) are bounded by these dashed lines indicating reasonable agreement with the previous measurements, which were used to construct this correlation. The high blowing cases (solid circles) show slightly lower evaporation rate than the low blowing cases at the same flow conditions indicating that blowing may indeed

isolate the droplet from the freestream turbulence. Clearly the evaporation rate is still larger than for the laminar flow case, so blowing does not completely isolate the droplet from the freestream turbulence.

An ASSERT project was recently initiated to address the second goal of this research program; gaining physical insight into why such mild gas phase turbulence has such a large effect on evaporation rate. Here, planar laser induced fluorescence (PLIF) measurements were made to obtain qualitative concentration measurements of the gaseous boundary layer surrounding the droplet. A schematic diagram of the PLIF setup is shown in Figure 4. The beam waist at the droplet position is approximately 16.5 μm with this system. Both acetone droplets and naphthalene spheres (as model evaporating "droplets") were used. Naphthalene was chosen because naphthalene fluoresces when irradiated with ultraviolet laser radiation and because it sublimes at atmospheric pressure and room temperature. In addition, unlike with acetone droplets, the use of naphthalene mitigates large fluorescence signals from the liquid phase and also the lensing effect due to the gas-liquid interface. This study was undertaken so that the shape and structure the gas phase acetone and naphthalene concentration boundary layer could be determined. Figure 5 shows a series of 3 naphthalene PLIF images made in both laminar and turbulent air at 77 C. Low pass filtering was applied to these images to smooth the intensity distribution prior to assigning contour levels. Note that the left images (laminar air case) show very similar concentration boundary layer structure at the three different time instances. However, the right images (turbulent air case) show that the concentration boundary layer thickness on the wake side of the sphere varies significantly at the three different time instances. This suggests that the increased evaporation rate for the turbulent gas phase case may be due to an oscillating concentration boundary layer in the separation region (i.e. wake) behind the sphere. More PLIF measurements are being made to substantiate this claim. Unfortunately, it is difficult to increase the B number of naphthalene beyond the value given in Figure 5 since naphthalene melts at 80.5 C. Acetone droplets will be used to study the high blowing number case.

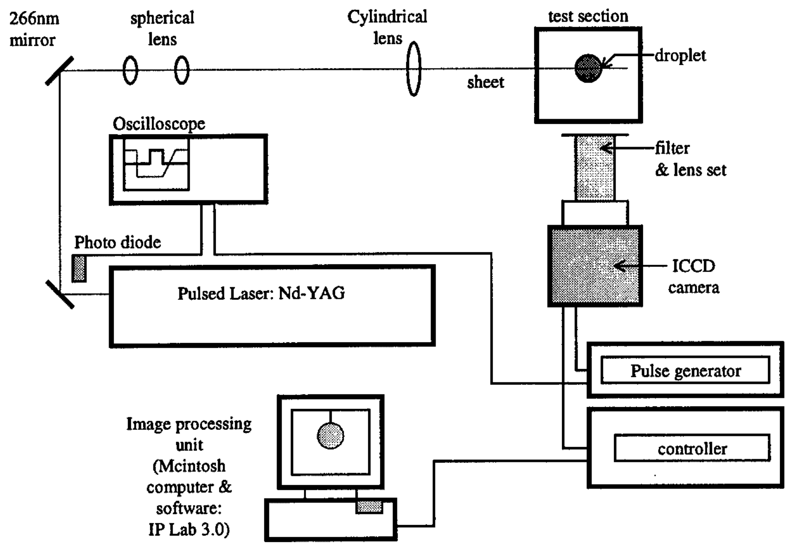
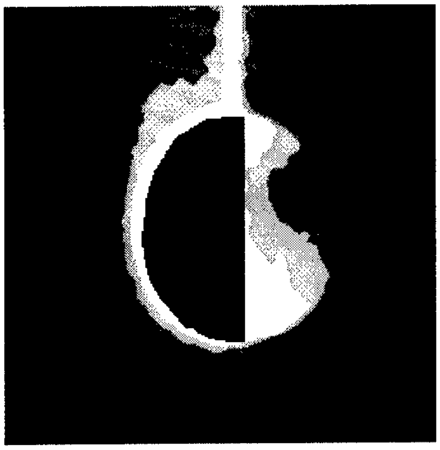


Figure 4. PLIF schematic

In conclusion, many improvements to the experimental apparatus and the experimental methodology were made during this project. The range of blowing number was extended and the issue of whether surface blowing isolates the evaporating droplet from the gas phase turbulence was raised. Finally, flow visualization studies have been initiated with the goal of understanding why evaporation rate is augmented by the gas phase turbulence. A rather complete understanding of this process is expected by the end of the ASSERT funding period as two PhD students are presently working to complete their dissertations.



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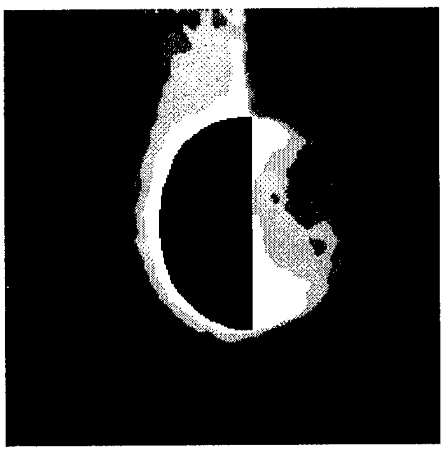

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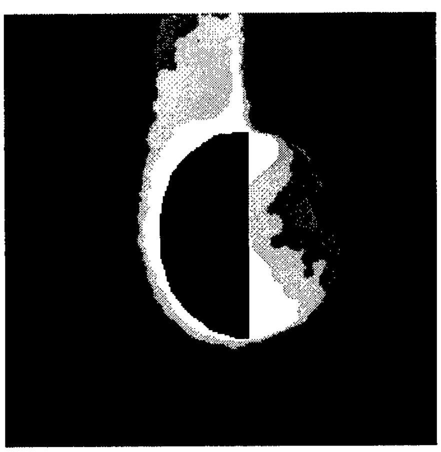

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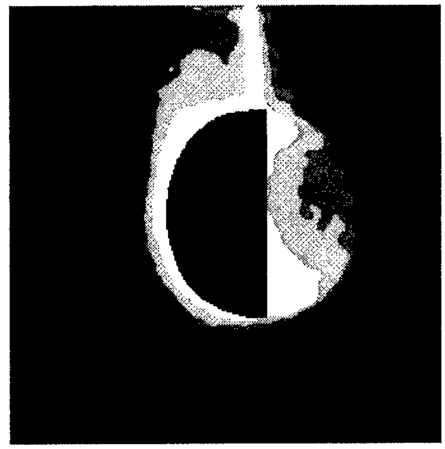
(a) Low turbulence (TI ~ 0.6%)



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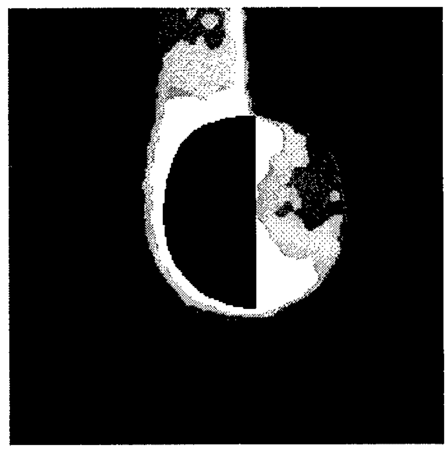

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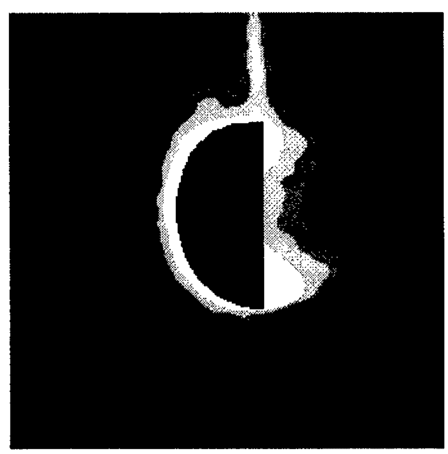

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(b) High turbulence (TI ~6.5%)

Figure 5. PLIF image of naphthalene droplet (Filtered, T_{air} ~ 77C, B_H ~ 0.0098)

LIST OF PUBLICATIONS AND TECHNICAL REPORTS

"The Flow Structure Around a Suspended Sphere at Low Reynolds Number in a Turbulent Freestream," with C. Eiamworawutthikul, accepted for publication in the 3rd ASME/JSME Joint Fluids Engineering Conference & FED Summer Meeting, San Francisco, CA.

"Spectral Estimations using Laser Doppler Anemometry with and without Bragg Cell Frequency Shifting," with C. Buchanan and C. Eiamworawutthikul, accepted for publication in the 3rd ASME/JSME Joint Fluids Engineering Conference & FED Summer Meeting, San Francisco, CA.

"Convective Heat and Mass Transfer from Single Evaporating Water, Methanol and Ethanol Droplets," with P. R. Yearling, *1995 ASME International Mechanical Engineering Congress and Exposition,* HTD-Vol. 321/FED-Vol. 233, pp. 33-38, 1995.

LIST OF INVENTIONS

None

PARTICIPATING SCIENTIFIC PERSONNEL

Four graduate students in the Mechanical and Aerospace Engineering Department at North Carolina State University were supported in part by this research grant. Their names, earned graduate degrees, graduation dates and thesis titles are given below.

1. Dr. Paul Yearling completed his thesis defense in August of 1995 and was awarded a Ph.D. from North Carolina State University entitled "Experimental Determination of Convective Heat and Mass Transfer Rates from Single Evaporating Liquid Droplets in a Turbulent Air Flow," in December of 1995. Following his thesis defense he was appointed to the position of visiting Assistant Professor in the Department of Mechanical and Aerospace Engineering Dept. He was supported half-time from 01 Jan 96 to 31 May 96 on this project.

2. Mr. Todd Jobin started his research program on 16 Aug. 1995 and was supported from 01 Jan 96 to 15 July 1997 on this project. He completed his thesis defense in July of 1997 and was awarded a Master of Science degree in Mechanical Engineering from North Carolina State University . His thesis is entitled, "Convective Heat and Mass Transfer from Evaporating Liquid Droplets in Turbulent Air Flow".

3. Ms. Crystal Buchanan, a Ph.D. candidate, started her research program on 16 Aug. 1996 and was supported from 16 Aug. 1996 to 14 Aug. 1997 on this project. She was supported after 14 Aug. 1997 using ASSERT funding associated with this parent grant.

4. Mr. Chonlathis Eiamworawutthikul, a Ph.D. candidate, started his research program on 16 Aug. 1997 and was supported from 16 Aug. 1997 to 31 Dec. 1997 on this project.

REFERENCES

Todd Jobin, 1997, " Convective Heat and Mass Transfer from Evaporating Liquid Droplets in Turbulent Air Flow," MSME Dissertation, North Carolina State University, July.

Renksizbulut, M., and Yuen, M.C., 1983, "Experimental Study of Droplet Evaporation in a High-Temperature Air Stream," *J. of Heat Transfer*, **105**, pp. 384-388.

Paul Yearling, 1995, "Experimental Determination of Convective Heat and Mass Transfer Rates from Single Evaporating Liquid Droplets in a Turbulent Air Flow," PhD Dissertation, North Carolina State University, August.